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A PRELIMINARY INVESTIGATION OF EXHAUST-GAS EJECTORS FOR GROUND COOLING

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE CONFIDENTIAL REPORT

A PRELIMINARY INVESTIGATION OF EXHAUST-GAS EJECTORS FOR GROUND COOLING

By Eugene J. Manganiello

SUMMARY

A preliminary investigation was made to determine the suitability of ejectors actuated by the exhaust of a radial air-cooled aircraft engine for providing engine cooling air at the ground condition. Various length and diameter ejectors were tested for varying engine power for: (1) nine ejectors, each being actuated by the exhaust of individual cylinders; and (2) three ejectors, each being actuated by the exhaust of groups of three cylinders.

The cooling-air pressure drop induced by ejector action increased with engine power and increased with increase of ejector length and diameter up to optimum values above which the pressure drop decreased. For equal ejector areas, the grouped system provided more cooling air than the individual ejectors. Diffuser exit sections markedly improved the ejector pumping. The pressure drops realized were of significant magnitude for cooling, a value of 4.65 inches of water being obtained for an ejector installation with diffusing exits.

INTRODUCTION

The increased output of aircraft engines in recent years has aggravated the difficulties of the cooling problem. Ground cooling, in particular, has been difficult to obtain in submerged installations, pusher-type installations, and some high-speed tractor installations. The possibility of the use of ejector pumps actuated by the engine exhaust has been suggested as a means of improving the situation.

Some experimental investigations of the ejector principle have been made in the past in connection with aircraft problems. References 1, 2, and 3 present results of tests of ejectors with regard to jet-thrust augmentation. The tests were conducted, for the most part, with small-scale models actuated by compressed air under steady-flow conditions. Reference 3 also includes the results of some tests with exhaust-gas ejectors. Reference 4 reports the results of an investigation of the design and operating conditions of small-scale compressed-air ejectors pertinent to their pumping, as well as to their thrust-augmentation, characteristics.

In view of the lack of experimental data directly applicable to the problem, an investigation was made to determine the efficacy of ejectors actuated by the exhaust of an aircraft engine in providing engine cooling air at the ground condition.

Tests were made of a propeller-loaded air-cooled engine of the 500-horsepower class mounted on an outdoor test stand. The pumping effectiveness of ejectors of different diameters was determined with varying lengths for: (1) nine ejectors, each actuated by the exhaust of individual cylinders; and (2) three ejectors, each actuated by the exhaust of a group of three cylinders. The pressure drop available for cooling was evaluated for conditions of ejector action alone and of combined ejector and propeller-slipstream effects.

This investigation was a preliminary survey of the problem to check the order of magnitude of the cooling-air pressure drop to be expected from ejector pumping and to determine its variation with change of the basic ejector dimensions.

APPARATUS AND METHODS

General Setup

A nine-cylinder radial air-cooled engine rated at 475 horsepower at an engine speed of 1900 rpm at sea level was used in these tests. This engine has a displacement volume of 1344 cubic inches, a compression ratio of 6.5, and a blower ratio of 13:1. The engine was mounted on an outdoor test stand that was provided with a scale for measuring engine torque. (See fig. 1.) Engine speed was measured with a tachometer, and manifold pressure was indicated by a mercury manometer. The engine was fitted with conventional cooling baffles and a conventional cowl that was completely closed off at the rear except for the ejector-stack openings.

Iron-constantan thermocouples were installed on the rear spark-plug gaskets and the flanges of each cylinder to provide an indication of the engine cooling. Gasoline having an octane rating of 100 and conforming to Army-Navy Fuel Specification No. AN-VV-F-781 was used in all tests.

The power was absorbed by adjustable propellers, the blades being set to give rated engine speed at rated power.

Individual Ejector Stacks

The exhaust stacks consisted of short lengths of straight tubing having necked-down exit sections with an area of about 2 square inches, this area being the minimum calculated value resulting in zero loss of engine power due to back pressure (reference 5). As shown in figure 2(a) the exhaust discharged into the center of the entrance sections of the ejector stacks, which consisted of straight lengths of sheet-metal tubing. The symbols used in figure 2 and later figures should be evident from the sketches; they are defined in the appendix. The dimensions of the entrance sections for the ejectors of 4- and 6-inch diameters are shown in figure 2(b). A rounded, or bell-shaped, entrance section was used for the ejectors of 4-inch diameter. Reference 2 indicates, however, that the shape of entrance is not critical; hence, straight conical entrance sections were used for all other ejectors tested.

In order to prevent the aerodynamic effects of the propeller slipstream from influencing the test results, a pusher propeller was used and a housing was built around the engine cowl. (See fig. 2(a).) The housing provided an annular passage for the engine cooling air with entrance at the rear of the cowling where the propeller effects were negligible, as determined by a pressure-head survey.

The cooling-air pressure drop across the engine baffles ΔP_b was measured at eight locations by means of pressure tubes and alcohol manometers. Three of the static-head tubes installed at the rear of the baffles were also utilized to indicate the total-pressure drop ΔP_t effected by ejector action. Pressure determinations were also made ahead of the engine (three locations), at the rear of the cowling where the cooling air entered (three locations), and at the end of one of the ejector stacks. The locations at which pressure measurements were made are shown schematically in figure 2(a).

Ejector stacks of 6- and 4-inch diameters and of lengths varying from 4 to 36 inches were tested for a range of engine power from 80 to 475 horsepower. Under the conditions of pusher propeller and housed cowl, the cooling-air pressure drop resulting from ejector action was insufficient to permit steady-state engine operation without excessive cylinder temperatures. The test procedure adopted to obviate this difficulty consisted of varying the engine power steadily from idling to full load and holding it constant at each of the test points only long enough to take photographic records of the manometers and the tachometer and to take simultaneous readings of the torque scale. Two series of runs were made for each ejector combination. Parallel series of tests were made with the ejectors of 6-inch diameter to obtain the combined effect of ejector and propeller-slipstream action. For these tests the cowl housing was removed and the pusher propeller was replaced with a tractor propeller. The test procedure was similar to that of the previous tests except that the engine power at each test point was maintained for an appreciable time interval without overheating the engine.

Group Ejector Stacks

The exhaust stacks of the nine cylinders were combined in groups of three to actuate three ejectors (fig. 3). Cylinders 1, 4, and 7 constituted the first group; cylinders 2, 5, and 8, the second; and cylinders 3, 6, and 9, the third. This arrangement resulted in equally spaced firing intervals of the cylinders in each group. The exhaust stacks connecting the cylinders to the ejectors were kept as free of sharp bends as was consistent with the physical limitations of the setup. The exit sections, which were of the same diameter as those in the individual-ejector tests, were set at the approximate center of the ejector entrance cones.

In view of the cooling difficulties encountered in the individual-ejector tests with the pusher propeller and the cowl housing, the grouped-ejector tests were made with a tractor propeller and no cowl housing. In order to provide information for isolating the effects of the propeller slipstream on the cooling-air pressure drop, a more extensive pressure survey was made. Pressure measurements were made at three locations in front of the engine and at eight locations across the baffles; all the tubes at the rear of the baffles were also used to indicate the pressure at the rear of the engine with respect to the atmosphere. Total-pressure P_o and static-pressure P_s

measurements were made at the downstream end of each ejector entrance section and static-pressure P_e measurements were made of the air at the exit section of each ejector.

Ejectors of 6-, $7\frac{1}{2}$-, and $8\frac{1}{2}$-inch diameters were tested for lengths from 4 to 36 inches over a range of engine power from 100 to 450 horsepower. Ejectors of $9\frac{1}{2}$-inch diameter were tested for lengths from 4 to 120 inches. The characteristics of the ejectors of $9\frac{1}{2}$-inch diameter were also determined for conditions of restricted exit sections in order to obtain data for correcting the test results to atmospheric pressure at exit. (See appendix for method of correcting results.) The two restrictions tested consisted of conical sections of $8\frac{1}{2}$-inch and $7\frac{1}{2}$-inch diameters at their exit ends. An additional test was made of the ejectors of $9\frac{1}{2}$-inch diameter when fitted with diffusers of $13\frac{1}{2}$-inch exit diameter and 30-inch length.

The engine cooling was adequate in these tests and therefore permitted the attaining of equilibrium conditions for each test point before data were recorded. Manometer readings were taken photographically and readings of engine speed, torque, and temperature were taken visually.

RESULTS AND DISCUSSION

Individual Ejectors

The total-pressure drop of the cooling air from the front to the rear of the engine baffles ΔP_t obtained in the housed-cowl tests is attributed entirely to the ejectors and may be taken as a measure of their performance. This total-pressure drop slightly exceeds the cooling-air pressure drop across the engine baffles ΔP_b because of the losses involved in the annular entrance passage provided between the cowl and the exterior housing.

The variation of total-pressure drop ΔP_t with engine horsepower for various lengths of the ejectors of 4-inch diameter is shown in figure 4(a). The increase of pressure drop with increase in horsepower results from the greater energy contained in the exhaust gas at the higher powers; whereas, the increase of pressure drop with increased ejector length is explained by the

mixing-length requirement for transfer of the energy of the exhaust gas to the cooling air. It is noted that the pressure drops are insufficient for satisfactory cooling. Similar results are obtained for the ejectors of 6-inch diameter (fig. 4(b)).

Comparison of the results of the ejectors of 4- and 6-inch diameters is given in figure 5, which is a cross plot of figures 4(a) and 4(b) with total-pressure drop plotted against length-diameter ratio at constant engine power of 450 brake horsepower. Also included in figure 5 are the results of the tests made of the combined ejector and propeller-slipstream pumping action. Greater cooling-air pressure drops are realized with the larger-diameter-ejector system and with increasing length. The pressure drop tends to level off at increasing length-diameter ratio owing to the diminishing improvement in energy transfer with increasing mixing length and to increasing friction losses. Evidently, the optimum length for these ejectors had not quite been reached in the tests.

The cooling-air flow is increased by incorporating the propeller-slipstream effects with the ejector action, a pressure drop of 3.7 inches of water resulting at a length-diameter ratio of 6 as compared with 2.6 inches of water for ejector action alone. Because the separate effects do not add algebraically when combined, the propeller slipstream alone would provide more pressure drop than is indicated by the difference of 1.1 between 3.7 and 2.6 inches of water. For example, at zero ejector length there is no pressure drop due to ejector action; hence, the pressure drop of 2 inches of water indicated for the combined ejector and propeller effects is evidently entirely attributable to propeller-slipstream effects.

The pressure drop of the combined ejector and propeller action levels off at shorter ejector lengths than the pressure drop of the ejector alone, owing to the greater friction associated with the larger air flows.

It is noted that the cooling-air flow due to propeller action is the resultant of two effects: (1) an increase in static pressure directly behind the propeller and acting at the front of the engine, and (2) a decrease in static pressure at the rear of the cowl and acting at the ejector exits. The second effect is greater in these tests than would prevail in some conventional propeller-nacelle combinations owing to the absence of an afterbody on the test installation. Use of cowl flaps on conventional nacelles, however, permits the obtaining of static pressures at the cowl exit of even lower values than existed in the test setup.

Grouped Ejectors

The cooling-air pressure drop ΔP_b obtained in the grouped-ejector tests is the resultant of both ejector and propeller-slipstream effects. The pressure drop attributed to ejector action alone $\Delta P_b'$ may be calculated from ΔP_b and a knowledge of the pressures at various points throughout the system. The method of calculating $\Delta P_b'$ is shown in the appendix.

The variation of pressure drop due to ejector action $\Delta P_b'$ with engine horsepower for various lengths of ejectors of 6-, $7\frac{1}{2}$-, $8\frac{1}{2}$-, and $9\frac{1}{2}$-inch diameters is shown in figures 6(a) to 6(d), respectively. The curves are, in general, similar to those of the individual ejector tests, showing an increase in pressure drop with increase in engine power and ejector length.

Figure 7(a) is a cross plot of figures 6(a) to 6(d) in which cooling-air pressure drop due to ejector action $\Delta P_b'$ is plotted against length-diameter ratio at constant engine power of 450 brake horsepower. The total pressure drops, ΔP_b (ejector plus propeller-slipstream effects), are plotted in a similar manner in figure 7(b).

Figure 7(a) indicates that the values of $\Delta P_b'$ increase with increase of ejector diameter at the higher values of length-diameter ratio but decrease with increase of ejector diameter at the lower values. The last-mentioned effect is somewhat unexpected but may possibly be due to better mixing effectiveness with smaller-diameter ejectors for the shorter lengths.

The performance of the ejector of $9\frac{1}{2}$-inch diameter, which was investigated over a larger range of lengths than the ejectors of smaller diameters, is seen to have definitely leveled off at a length-diameter value of about 6, providing a maximum pressure drop of about 3.3 inches of water. Comparison of the $8\frac{1}{2}$- and $9\frac{1}{2}$-inch-diameter curves indicates that further increase in diameter would be unlikely to increase the ejector pumping appreciably.

With reference to the curves of combined ejector and propeller-slipstream action (fig. 7(b)), it is seen that the pressure drops for the larger ejectors remain higher than those

for the smaller-diameter ejectors down to lower values of length-diameter ratio than for the ejectors alone. This fact may be explained by the increase in propeller pumping with increased exit area. The greater effect of diameter on pressure drop with the combined ejector and propeller-slipstream action, as compared with the ejectors alone, may be attributed to the same effect.

The performance of the ejector of $9\frac{1}{2}$-inch diameter is seen not only to have leveled off but to have started decreasing with increased length in the range tested, illustrating the effect of greater friction at higher air flows. A maximum pressure drop of about 5.4 inches of water is realized, which is an increase of 2.1 inches of water over the performance of the ejector alone.

The use of a diffuser exit section results in a marked improvement in ejector performance. From figure 6(d) it is seen that a cooling-air pressure drop of 4.65 inches of water is obtained at 450 brake horsepower for the ejector of $9\frac{1}{2}$-inch diameter by 36-inch length when fitted with diffuser exits of $13\frac{1}{2}$-inch diameter by 30-inch length.

The corresponding ejector plus propeller-slipstream pressure drop for these diffuser ejectors was 6.75 inches of water. The performance of the ejectors of $9\frac{1}{2}$-inch diameter (without diffusers) of the same over-all length is found to be 3.1 and 5.2 inches of water for the ejectors alone and ejectors plus slipstream, respectively (fig. 7). The increased performance of the diffuser ejectors is attributable to the pressure-recovery characteristics of the diffuser. Obviously, the diffuser is a very important adjunct of the ejector.

From a comparison of figures 5 and 7 it is seen that the individual ejectors provide slightly higher cooling-air pressure drops than the grouped ejectors for the 6-inch-diameter stacks (the only size common to both systems). It is noted, however, that the total ejector area of the individual system is three times that of the grouped system. For a case of almost equal total ejector area (specifically, the $9\frac{1}{2}$-in.-diam. grouped ejectors and the 6-in.-diam. individual ejectors), it is apparent that the grouped system results in higher maximum pressure drops than the individual system. Since small cowling

exit area is required for the airplane in the high-speed condition, grouped-ejector systems will probably be preferable to individual ejectors.

Satisfactory cooling for the engine used in these tests was obtained with about 2 inches of water pressure drop at 450-brake-horsepower output. In view of the magnitude of the pressure drops obtained in these tests, it is apparent that exhaust-gas-actuated ejectors offer a method of providing satisfactory cooling for the ground condition and should be of particular advantage for submerged and pusher-propeller installations.

Admittedly, these tests were of a preliminary nature and a more complete investigation of ejectors is desirable. Additional tests might well include an extensive survey of ejector size and shape and diffusing exits with engines of current horsepower ratings at various flight speeds and altitudes.

CONCLUSIONS

From tests of a nine-cylinder radial air-cooled engine of 475 rated horsepower provided with ejectors actuated by exhaust gas, it has been concluded that:

1. Ejectors furnished a means of supplying the required engine cooling air at the ground condition.

2. The cooling-air pressure drop induced by ejector action increased with engine power.

3. The cooling-air pressure drop provided by the ejectors increased with increase of ejector diameter and length up to optimum values.

4. For equal total ejector cross-sectional area a grouped system of three ejectors, each actuated by the exhaust of three engine cylinders, provided higher cooling-air pressure drop than individual ejectors for each cylinder.

5. Diffuser exit sections considerably improved the performance of the ejectors.

6. A total cooling-air pressure drop of 6.75 inches of water was obtained at an engine power of 450 brake horsepower for ejectors fitted with diffuser exit sections; of this amount 4.65 inches of water is attributed to ejector action.

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APPENDIX

CORRECTION FOR PROPELLER-SLIPSTREAM EFFECTS

The cooling-air pressure drops ΔP_b obtained in the grouped-ejector tests were the result of both ejector and propeller-slipstream action. The measured ΔP_b may be corrected by a semiempirical method for the propeller-slipstream effects to obtain the pressure drop due to ejector action $\Delta P_b'$.

Static-Pressure Increase in Front of Engine

Consider first the increase in static pressure ahead of the engine due to the propeller slipstream. (See fig. 3.) The quantity of cooling-air flow Q is proportional to the square root of the pressure drop across the engine baffles

$$Q = K_1\sqrt{\Delta P_b} = K_1\sqrt{P_a - P_r} \tag{1}$$

where

P_a static pressure ahead of engine

P_r static pressure at rear of engine

and is proportional to the square root of the static-pressure drop from the rear of the engine to the front end of the ejector tube P_s

$$Q = K_2\sqrt{P_r - P_s} \tag{2}$$

From equations (1) and (2)

$$P_a - P_r = K_3(P_r - P_s) \tag{3}$$

which may be written

$$P_a - P_r = K_4(P_a - P_s)$$

or

$$\Delta P_b = K_4(P_a - P_s) \tag{4}$$

If the subscript i is used to denote measured, or indicated, values and the subscript c to denote values corrected to P_a reduced to atmospheric pressure, it follows that

$$\frac{\Delta P_{b_c}}{\Delta P_{b_i}} = \frac{P_{a_c} - P_{s_c}}{P_{a_i} - P_{s_i}} \tag{5}$$

For the small range of variation of P_a experienced in the in the tests, P_{s_c} may, as a good approximation, be taken equal to P_{s_i} because the effect of the change in P_a is to change the quantity of cooling-air flow Q; and P_s was observed to be substantially independent of Q for constant ejector conditions, as determined by the tests on the ejectors with restricted exit sections. Equation (5) thus becomes

$$\frac{\Delta P_{b_c}}{\Delta P_{b_i}} = \frac{P_{a_c} - P_{s_i}}{P_{a_i} - P_{s_i}} \tag{6}$$

Equation (6) permits a reduction of the measured pressure drops to the pressure drops that would exist were there no increase in static pressure over atmospheric in front of the engine. In the application of this correction to the test data, the value of P_{a_i} used was the difference between the observed values of ΔP_b and P_r. This difference was considered to be more accurate than the observed value of P_a (see fig. 3) because ΔP_b and P_r were obtained from averaging pressure readings at eight locations; whereas P_a was obtained from averaging pressures at three locations. It is noted that good agreement existed between the two values.

Static-Pressure Decrease at Ejector Exit

The correction for reduction in static pressure in the region of the ejector exits P_e caused by the propeller slipstream was obtained from a graphical analysis of the data.

The cooling-air pressure drops ΔP_{b_c} were plotted against the static pressure at the entrance end of the ejectors P_s and were found to yield straight-line relationships for ejectors of each diameter (see fig. 8), which indicates the following expressions:

$$\left(\Delta P_{b_c}\right)_2 - \left(\Delta P_{b_c}\right)_1 = - m \left(P_{s_2} - P_{s_1}\right) \tag{7}$$

where m is the slope of the lines and depends on ejector diameter and subscripts 1 and 2 refer to specific points on the curve. It is noted that P_s in figure 8 is given in inches of water vacuum and is thus consistent with the negative slope indicated in equation (7).

The tests of the ejectors with conically restricted exit sections gave the variation of pressure rise in the ejector $(P_e - P_s)$ for variation of exit pressures from several inches of water below atmospheric to an inch above. It is noted that, for the restricted-exit tests, P_e is the static pressure existing at the exit end of the ejector just upstream of the restriction. The variation of pressure rise in the ejector stack $(P_e - P_s)$ with engine power was found to fit a single curve for each ejector length for this range of exit pressures. Figure 9 illustrates one of these curves. Hence $(P_e - P_s)$ can be considered independent of P_e for a specified ejector, giving

$$P_{e_1} - P_{s_1} = P_{e_2} - P_{s_2} \tag{8}$$

From equations (7) and (8) there is obtained

$$\left(\Delta P_{b_c}\right)_2 - \left(\Delta P_{b_c}\right)_1 = - m \left(P_{e_2} - P_{e_1}\right) \tag{9}$$

or, designating $\Delta P_b'$ as the cooling-air pressure drop corresponding to an ejector exit pressure P_{e_c} (equal to atmospheric) and ΔP_{b_c} as the previously noted cooling-air pressure drop corresponding to the measured ejector-exit pressure P_{e_i} (less than atmospheric)

$$\Delta P_b' = \Delta P_{b_c} - m \left(P_{e_c} - P_{e_i}\right) \tag{10}$$

Combining equations (6) and (10)

$$\Delta P_b' = \Delta P_{b_i} \left(\frac{P_{a_c} - P_{s_i}}{P_{a_i} - P_{s_i}}\right) - m \left(P_{e_c} - P_{e_i}\right) \tag{11}$$

Equation (11) provides the correction of the measured pressure drops for propeller-slipstream effects.

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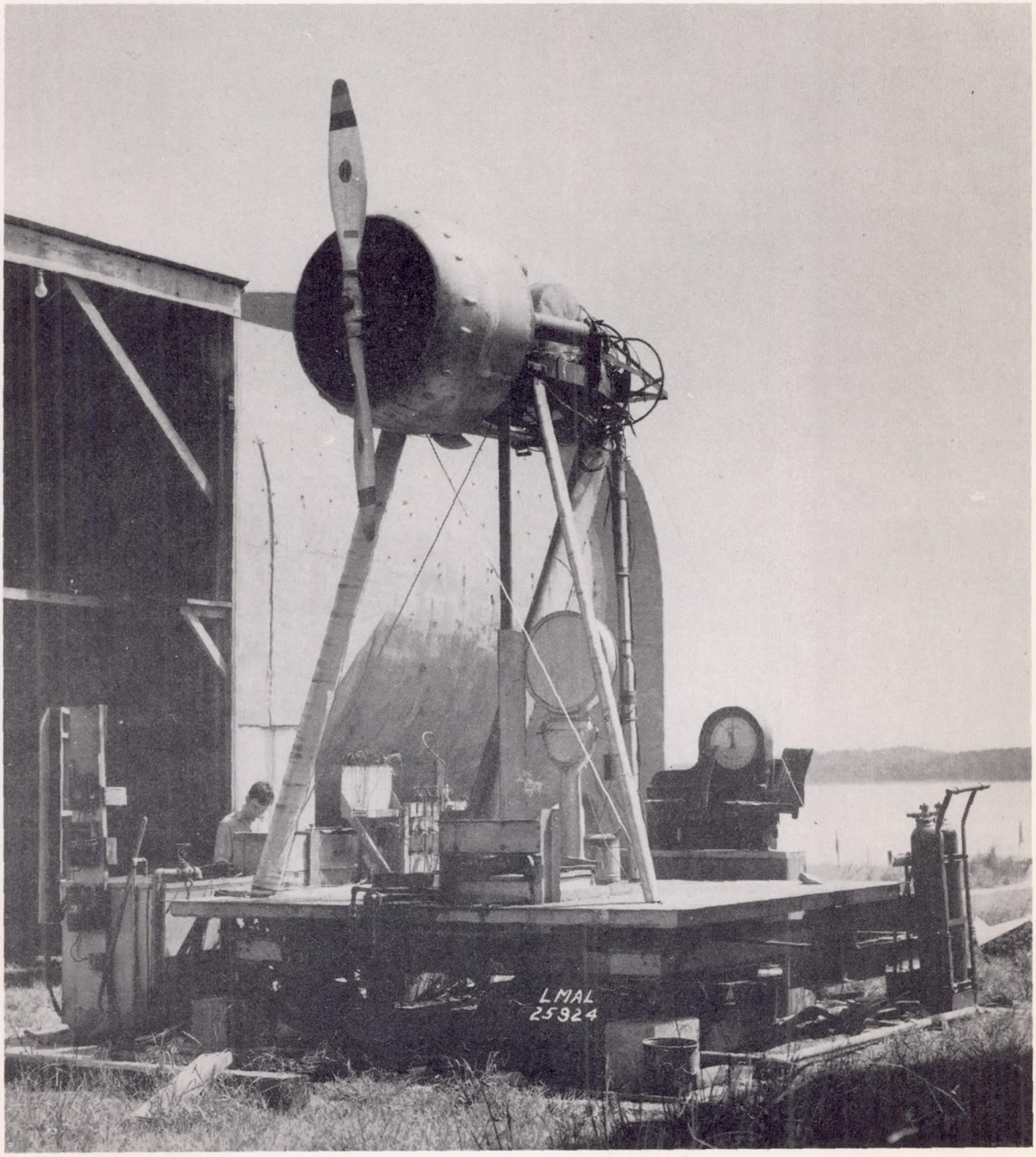
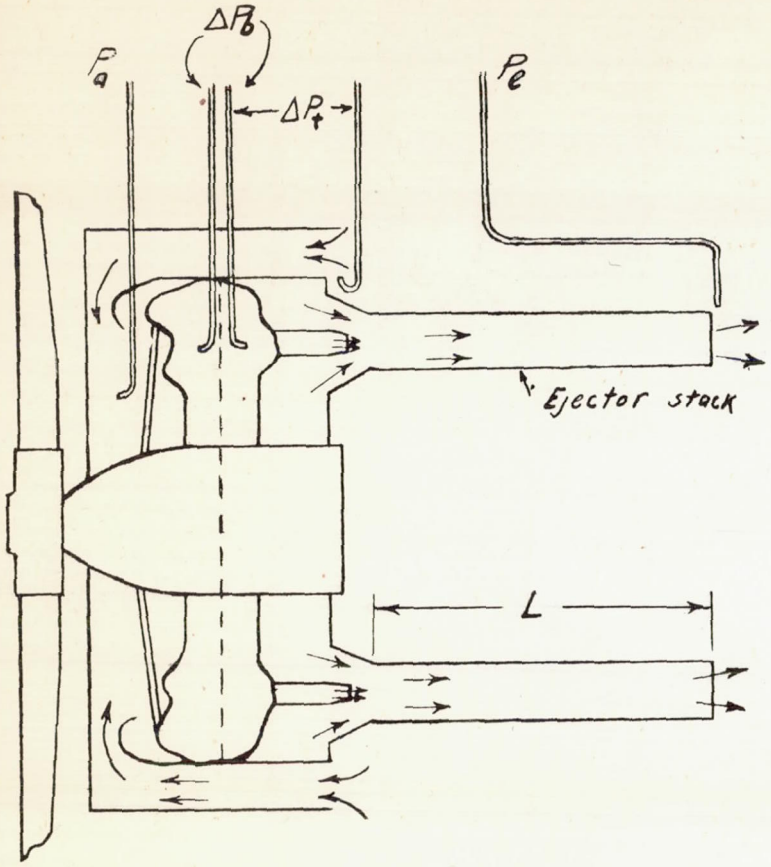
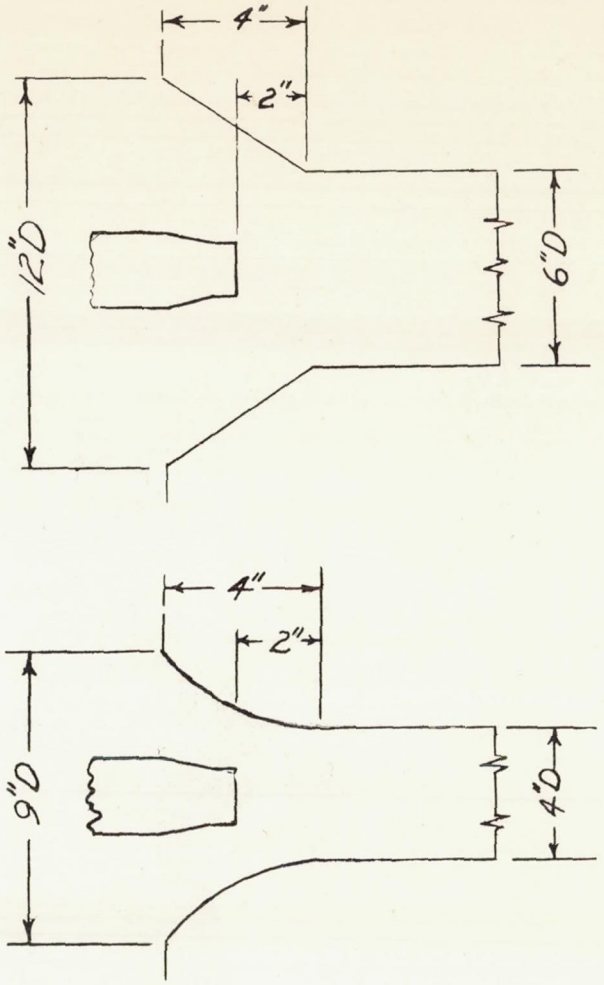


Figure 1. - The engine and outdoor test stand.



(a) General arrangement.



(b) Entrance-section details.

Figure 2. - Individual-ejector system.

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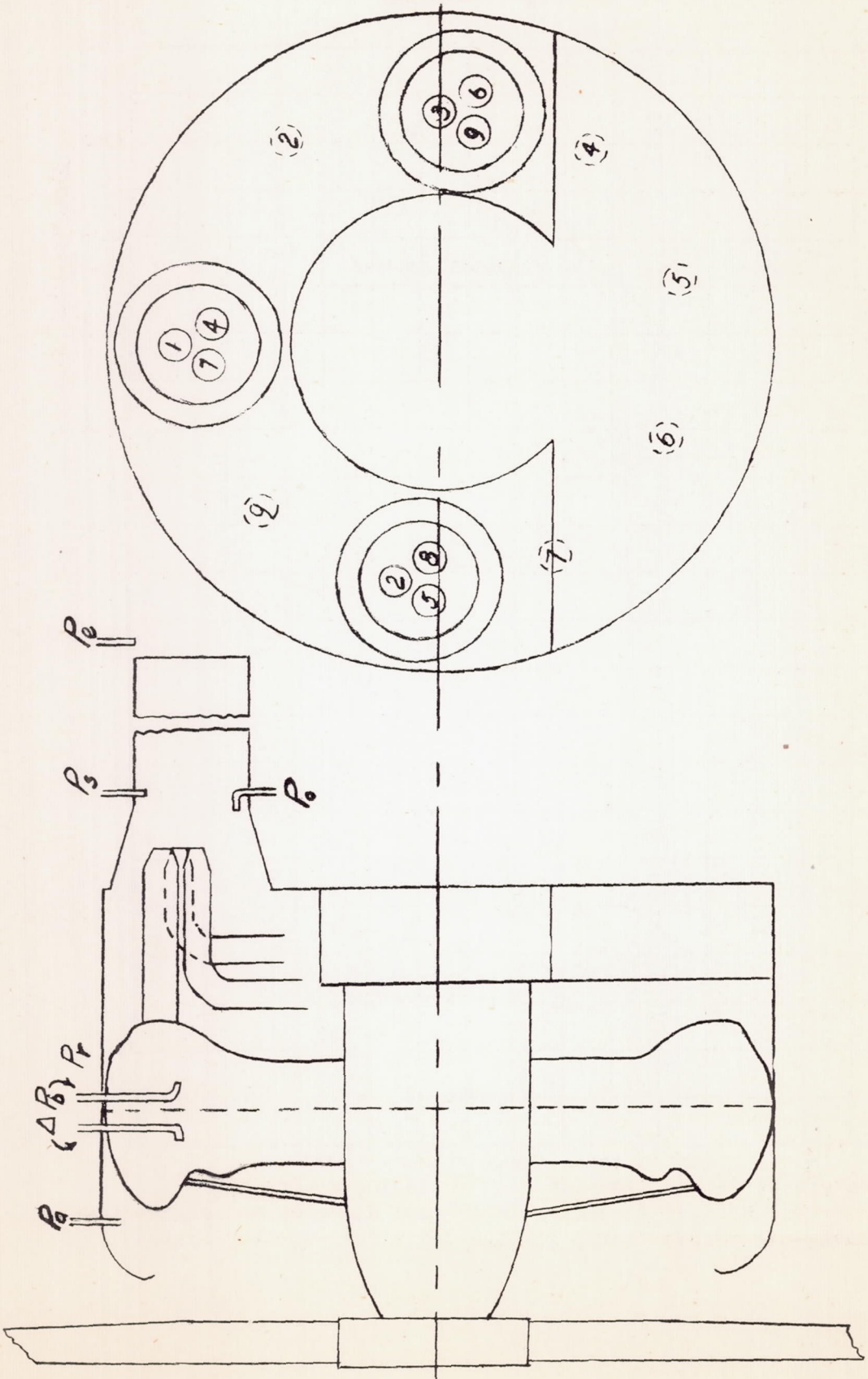
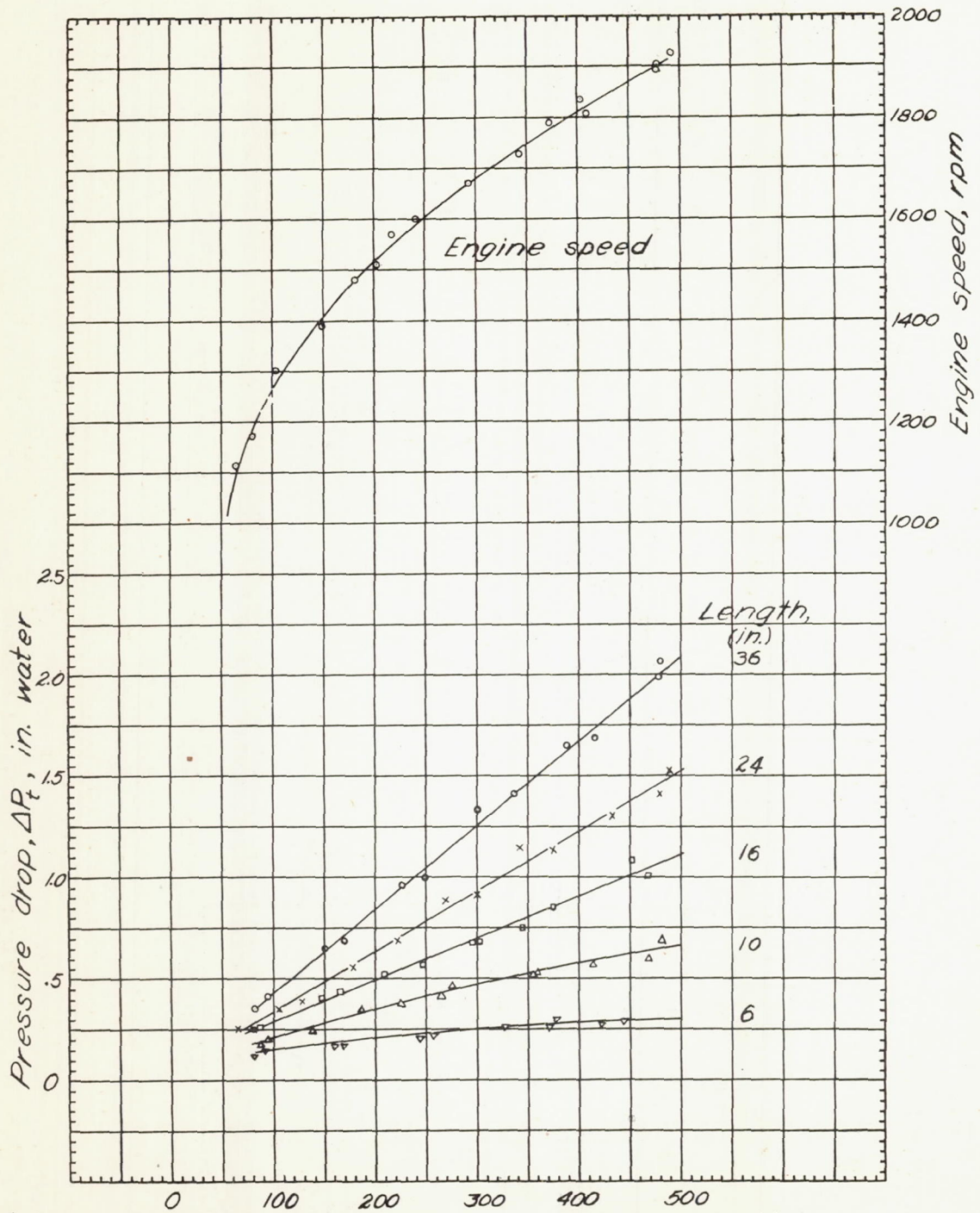
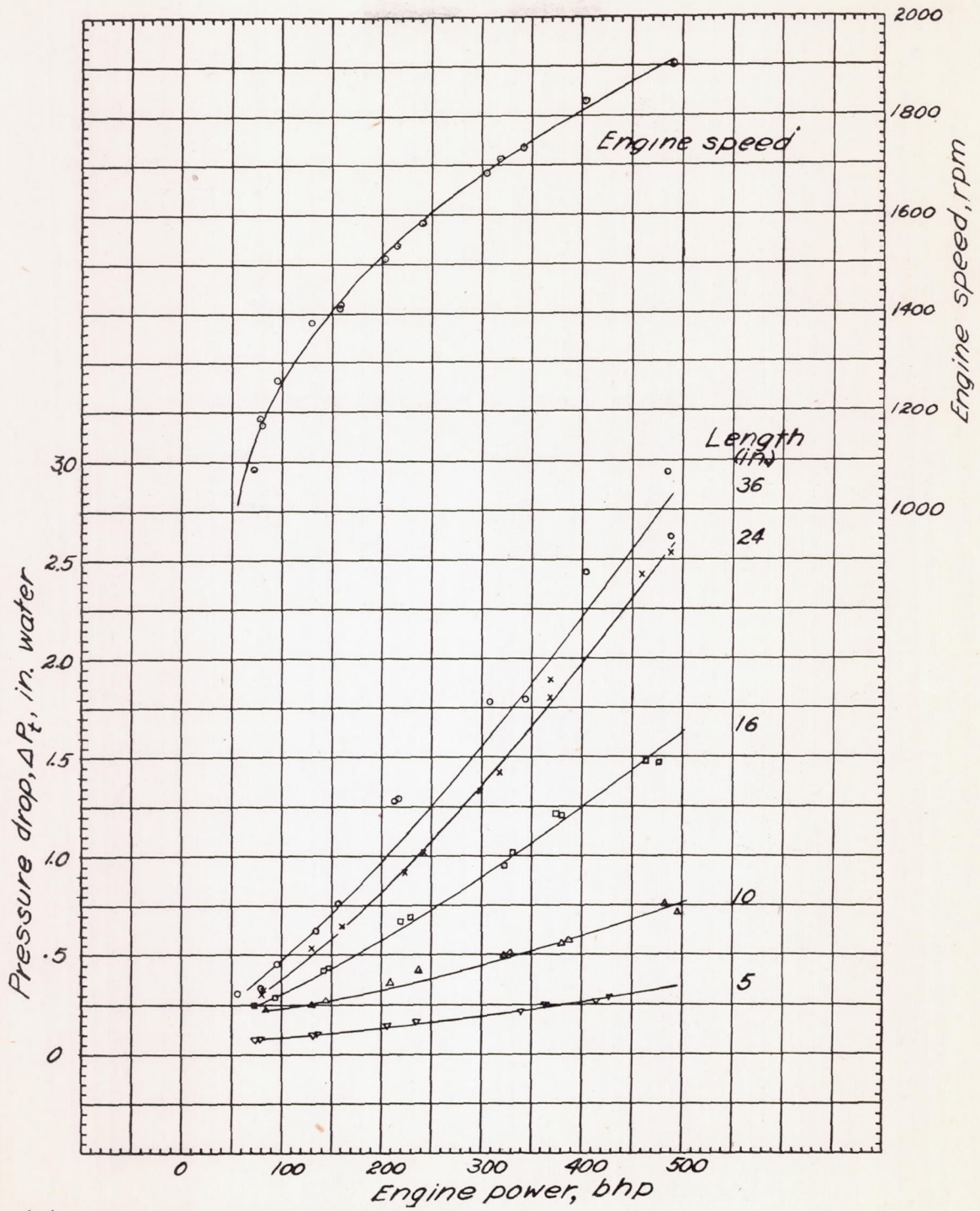


Figure 3. - Grouped-ejector system.



(a) Ejectors of 4-inch diameter.

Figure 4. - The effect of ejector length and diameter and engine power on cooling-air pressure drop for the individual-ejector system.



(b) Ejectors of 6-inch diameter.

Figure 4. - Concluded. The effect of ejector length and diameter and engine power on cooling-air pressure drop for the individual-ejector system.

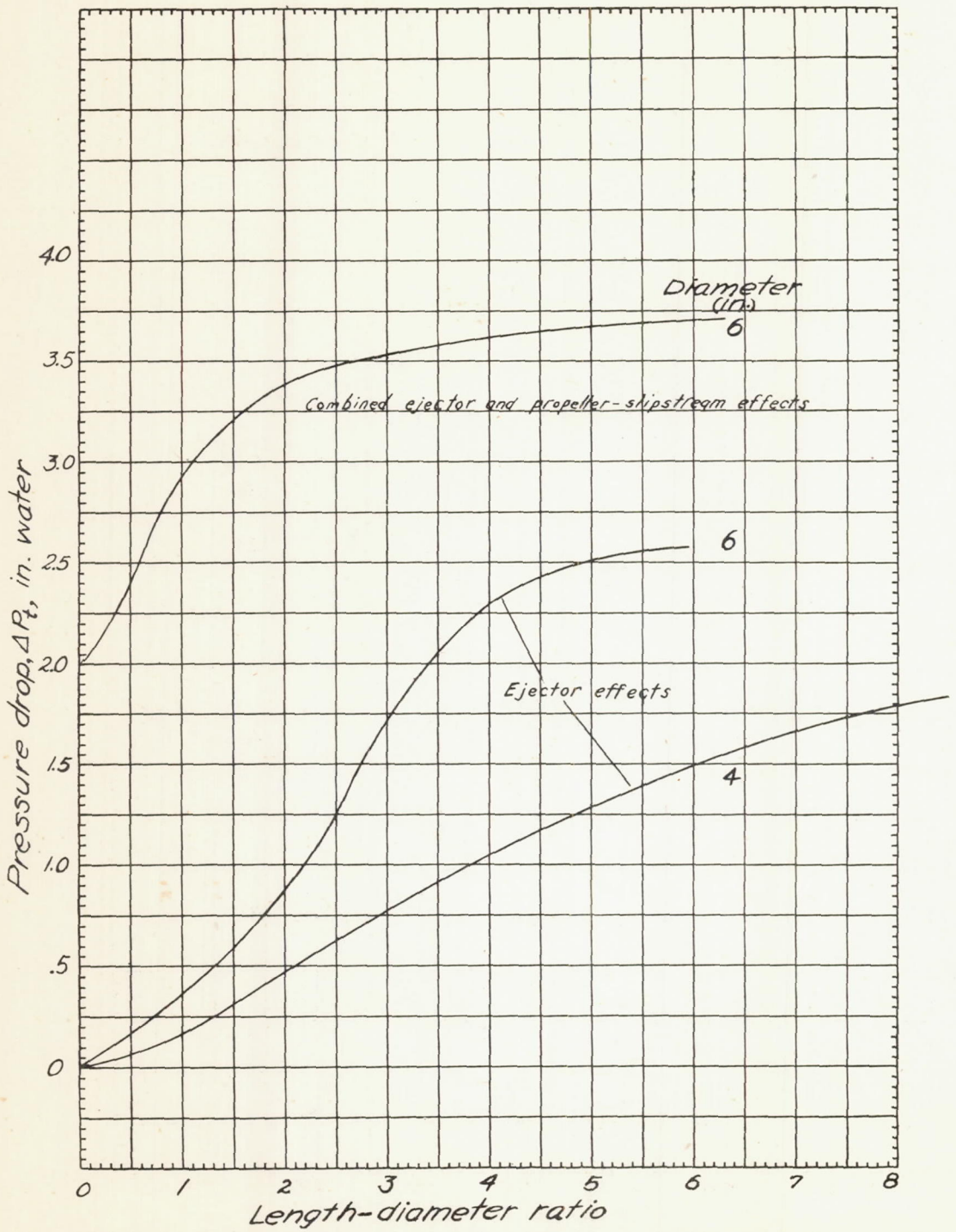
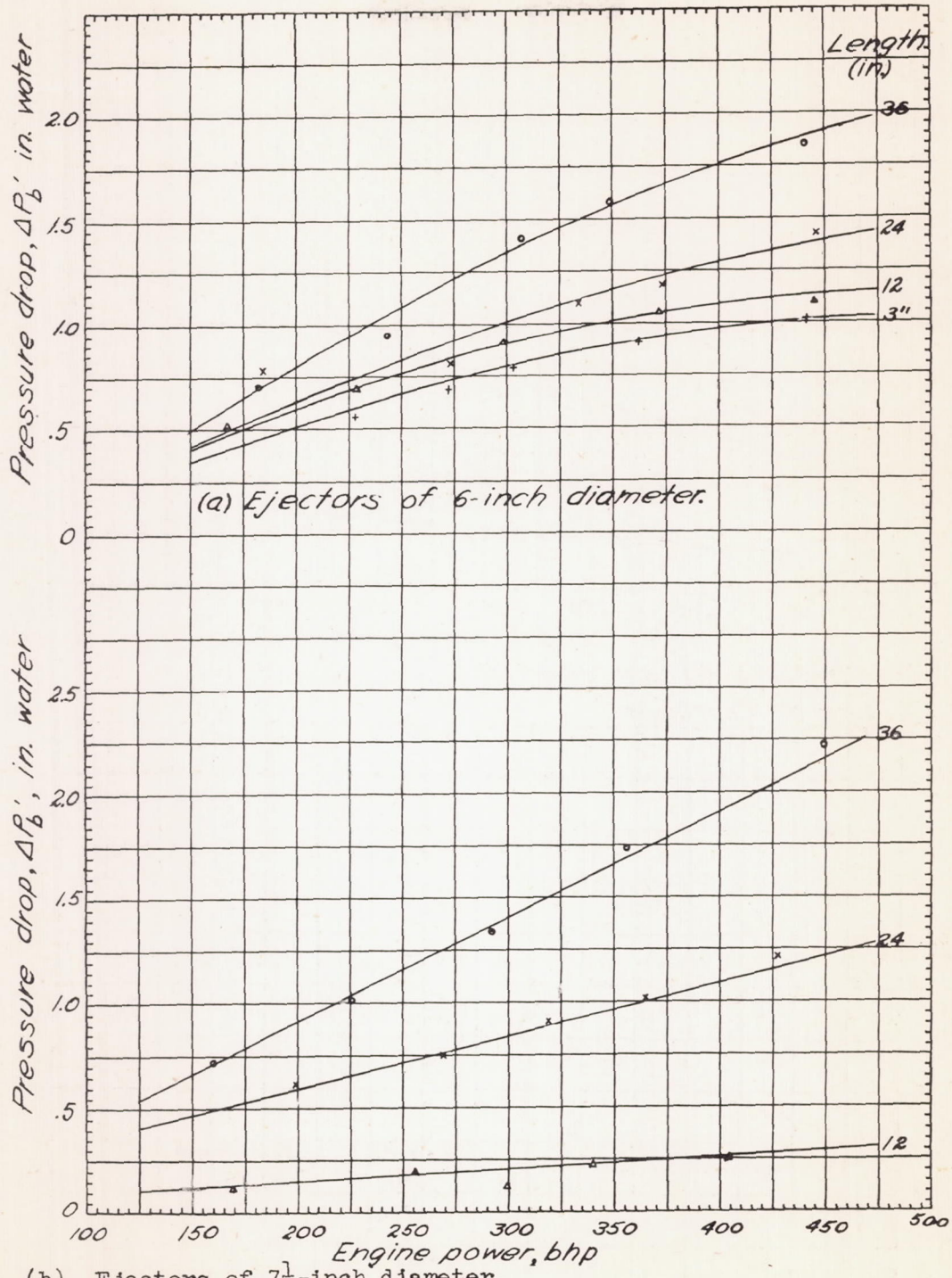
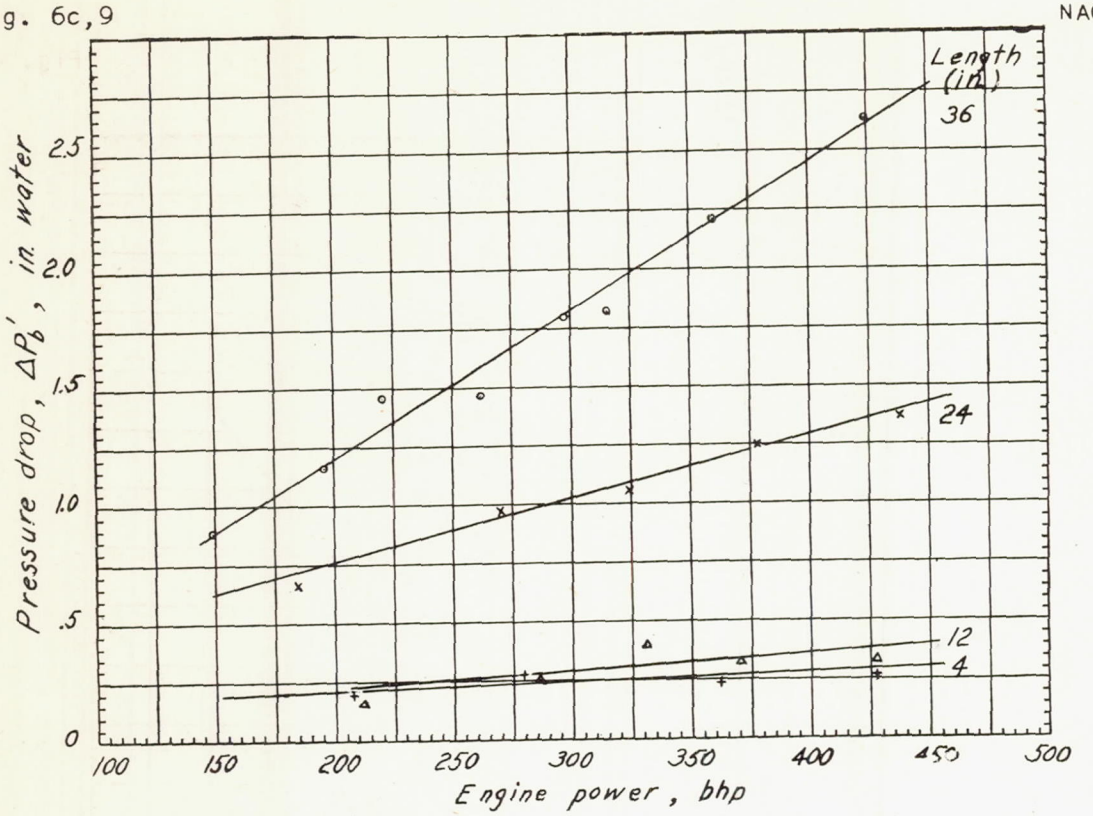


Figure 5. - The effect of length-diameter ratio on cooling-air pressure drop for individual-ejector system at 450 brake horsepower.



(b) Ejectors of $7\frac{1}{2}$-inch diameter.

Figure 6. - The effect of ejector length and diameter and engine power on cooling-air pressure drop for the grouped-ejector system.



(c) Ejector of $8\frac{1}{2}$-inch diameter.

Figure 6.- Continued

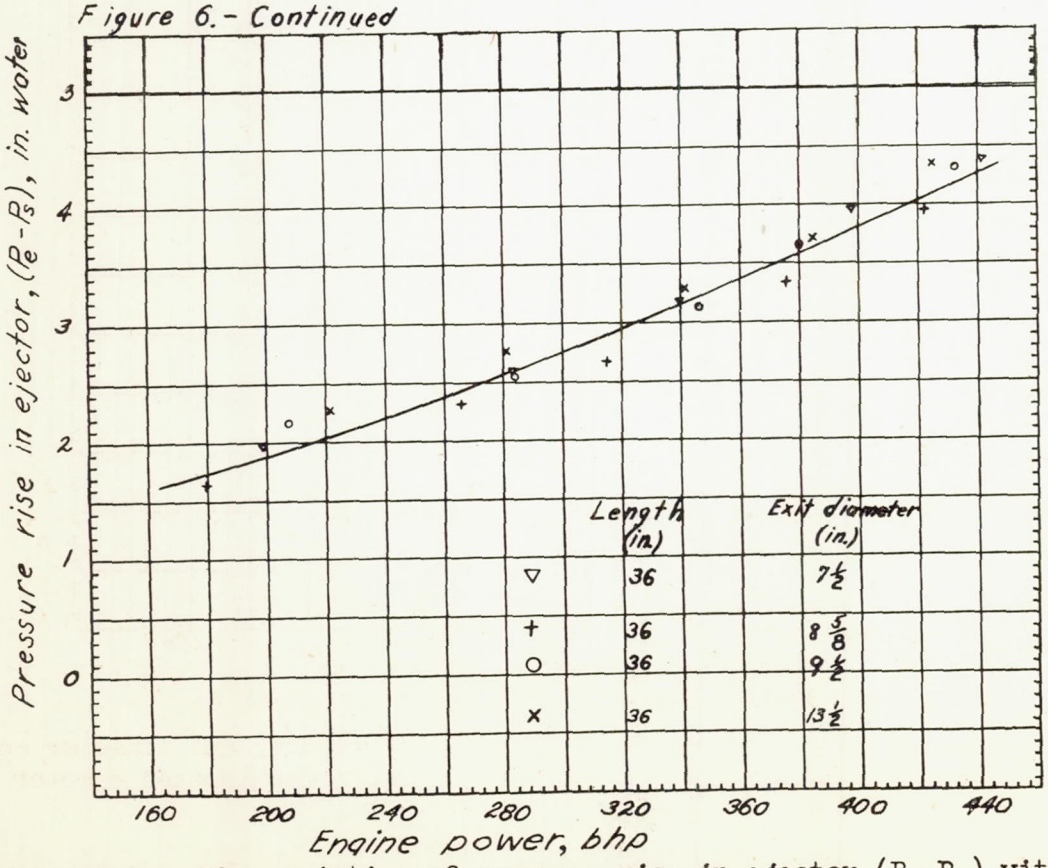
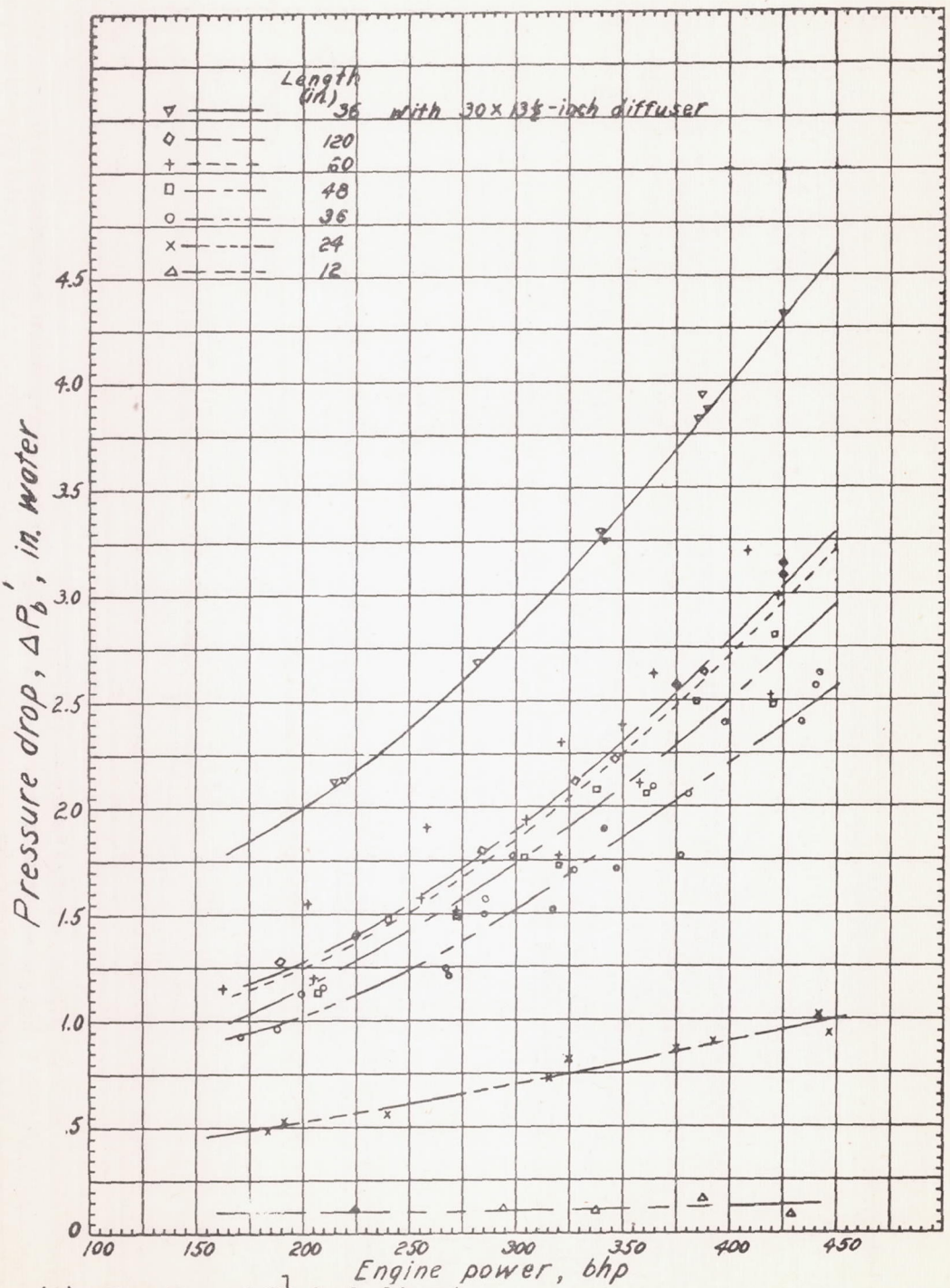


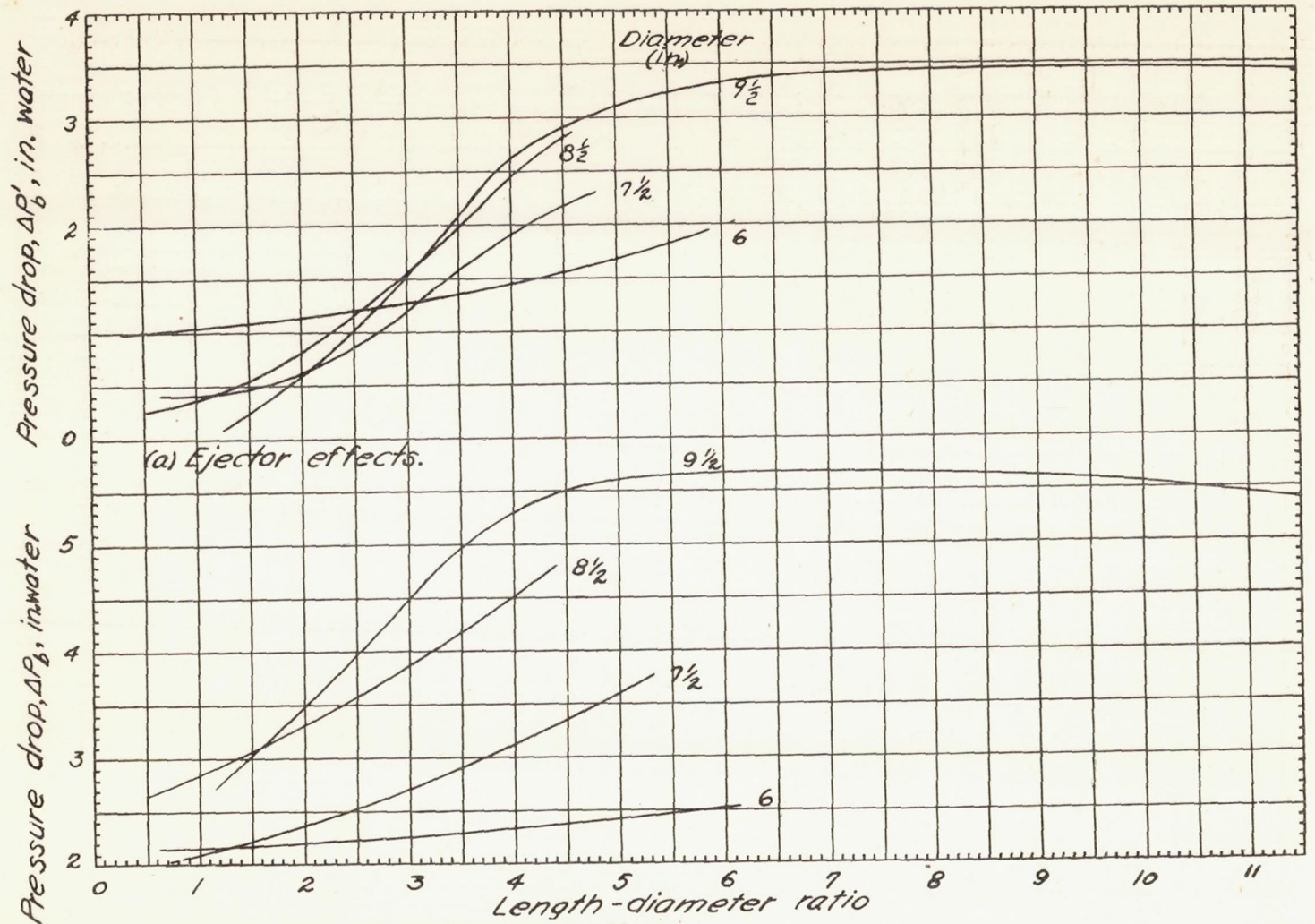
Figure 9. - The variation of pressure rise in ejector (P_e-P_s) with engine power for the grouped ejectors of $9\frac{1}{2}$-inch diameter.

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(d) Ejector of $9\frac{1}{2}$-inch diameter.

Figure 6. - Concluded. The effect of ejector length and diameter and engine power on cooling-air pressure drop for the grouped-ejector system.



(b) Combined ejector and propeller-slipstream effects.

Figure 7. - The effect of length-diameter ratio on cooling-air pressure drop for grouped-ejector system at 450 brake horsepower.

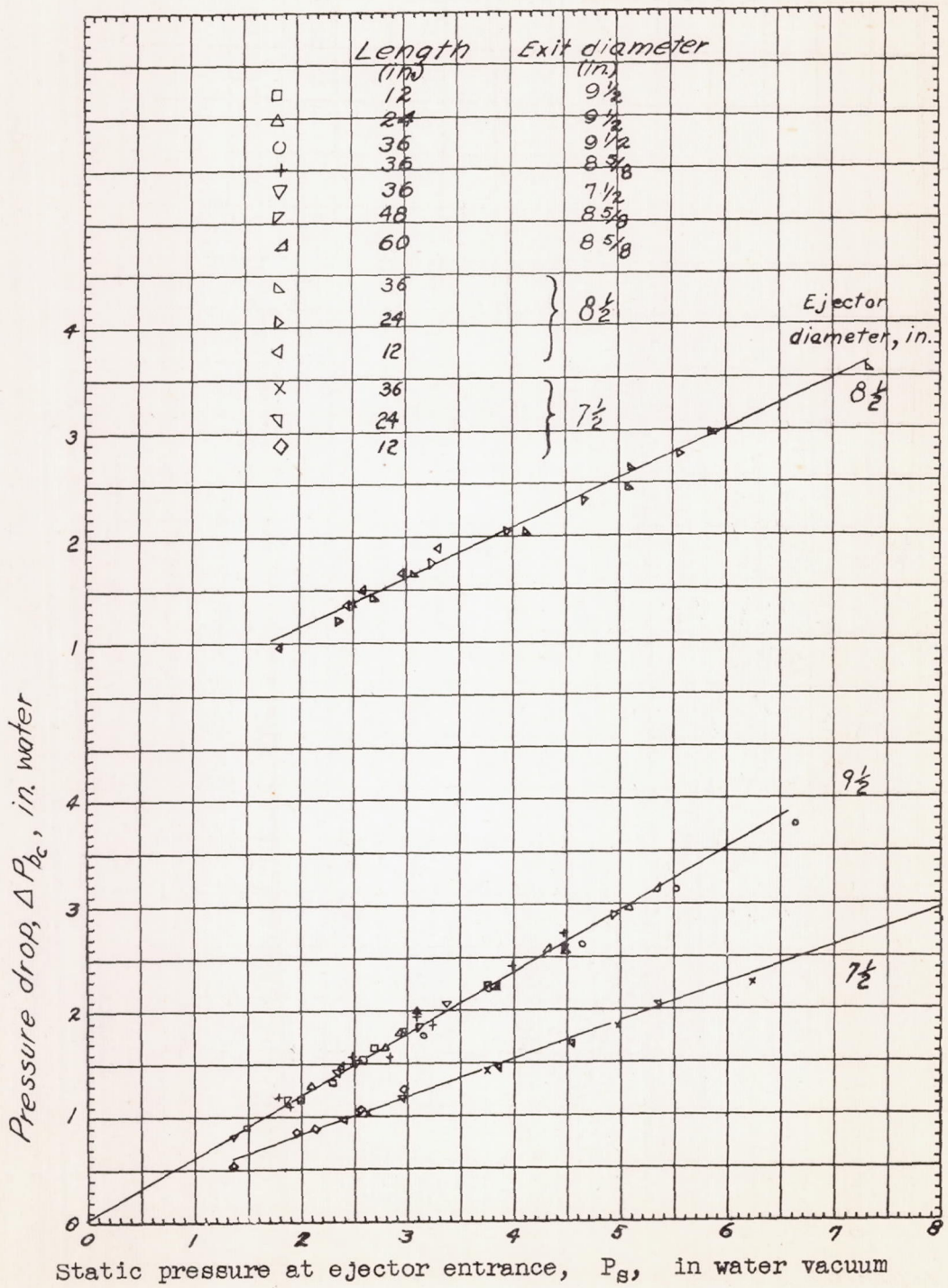


Figure 8. - The variation of pressure drop ΔP_{b_c} with static pressure at ejector entrance P_s for the grouped ejectors.